Experimental Investigation of Friction Coefficient and Wear Rate of Different Sliding Pairs

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Abstract: A series of experimental tests were carried out using turned and ground mild steel surfaces rubbing against smooth and rough mild steel conterfaces under different operating conditions on a pin-on-disc test rig. The test parameters include the sliding speed of 1–2 m/s, normal force of 10–20N and relative humidity of 70%. During testing, the friction coefficient and wear rate were recorded. The topography of worn surfaces was also observed with optical microscope. The average surface roughness of turned and ground mild steel were measured after friction test. The result displays that normal load, sliding speed and surface conditions of pin and disc have a distinct effect on the friction and wear behaviour of turned and ground mild steel rubbing against smooth and rough mild steel conterfaces. During this study, the effects of duration of rubbing on friction coefficient are also observed. Friction coefficient and wear rate of four types of disc-pin combinations such as ground-smooth, turned-smooth, ground-rough and turned-rough are observed under different normal loads and sliding velocities. Experimental results reveal that friction coefficient of mild steel for all types of disc-pin combinations decreases with the increase in normal load and sliding velocity. The magnitudes of friction coefficient are different for different disc-pin combinations. With increasing sliding velocity and normal load, wear rate of mild steel for different disc-pin combinations increases within the observed range.

Key words: Friction coefficient · Wear rate · Turned surface · Ground surface · Smooth surface · Rough surface · Mild steel

INTRODUCTION

Study of mechanics of friction and the relationship between friction and wear dates back to the sixteenth century, almost immediately after the invention of Newton's law of motion. It was observed by several researchers [1-14] that the variation of friction depends on interfacial conditions such as normal load, geometry, relative surface motion, sliding velocity, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, stick-slip, relative humidity, lubrication and vibration. Among these factors normal load and sliding velocity are the two major factors that play significant role for the variation of friction. In the case of materials with surface films which are either deliberately applied or produced by reaction with environment, the coefficient of friction may not remain constant as a function of load. Friction may increase or decrease as a result of increased normal load for different materials combinations. In many metal pairs, the friction coefficient is low at low loads and a transition occurs to a higher value as the normal load is increased. At low loads, the oxide film effectively separates two metal surfaces and there is little or no true metallic contact, hence the friction coefficient is low. At higher load conditions, the film breaks down, resulting in intimate metallic contact, which is responsible for higher friction [15]. It was observed that the coefficient of friction may be

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very low for very smooth surfaces and/or at loads down to micro-to nanonewton range [16,17]. At lower normal loads, the contact of the asperities is less and results in plowing action, increasing the friction coefficient. As the normal load increases, it results in better conformity of the contacting surfaces resulting in the reduced plowing action and friction coefficient. As the normal load is increased, an oxide layer may form on the surface due to rise of surface temperature and will provide lubricating action and reduce the friction [18]. Bhushan [19] and Blau [20] reported that increased surface roughening and a large quantity of wear debris are believed to be responsible for decrease in friction. The third law of friction, which states that friction is independent of velocity, is not generally valid. Friction may increase or decrease as a result of increased sliding velocity for different materials combinations. An increase in the temperature generally results in metal softening in the case of low melting point metals. An increase in temperature may result in solid-state phase transformation which may either improve or degrade mechanical properties [13]. The most drastic effect occurs if a metal approaches its melting point and its strength drops rapidly and thermal diffusion and creep phenomena become more important. The resulting increased adhesion at contacts and ductility lead to an increase in friction [13]. The increase in friction coefficient with sliding velocity due to more adhesion of counterface material (pin) on disc. Some results showed that the coefficient of kinetic friction as a function of sliding velocity generally has a negative slope. Changes in the sliding velocity result in a change in the shear rate which can influence the mechanical properties of the mating materials. The strength of many metals and nonmetals is greater at higher shear strain rates as stated by Bhushan and Jahsman [21, 22] which results in a lower real area of contact and a lower coefficient of friction in a dry contact. On the other hand, Bhushan reported that high normal pressures and high sliding speeds can result in high interface (flash) temperatures that can significantly reduce the strength of most materials [23]. Yet in some cases, localized surface melting reduces shear strength and friction drops to a low value determined by viscous forces in the liquid layer. Fridmen and Levesque [24] suggest that part of the observed friction reduction is due to negative slope of the dependence of the friction force upon velocity. The friction force is a function of velocity and time of contact. For most materials when the velocity increases, friction decreases and when duration of contact increases, friction increases. The dependence of friction

on velocity may be explained in the following way. When velocity increases, momentum transfer in the normal direction increases producing an upward force on the upper surface. This results in an increased separation between the two surfaces which will decrease the real area of contact. Contributing to the increased separation is the fact that at higher speeds, the time during which opposite asperities compress each other is reduced increasing the level on which the top surfaces moves.

It was reported [25-28] that friction coefficient of metals and alloys showed different behavior under different operating conditions. In spite of these investigations, the effects of normal load and sliding velocity on friction coefficient of mild steel, especially, under the turned and ground conditions sliding against mild steel rough and smooth counterfaces are yet to be clearly understood. Therefore, in this study, an attempt is made to investigate the effect of normal load and sliding velocity on the friction coefficient of mild steel (turned and ground surfaces) mating with rough and smooth mild steel counterfaces. The effects of duration of rubbing on friction coefficient is also be observed in this study. Moreover, the effects of normal load and sliding velocity on wear rate of mild steel are examined. It is expected that the applications of these results will contribute to the different concerned mechanical processes.

Nowadays, different steel combinations are widely used for sliding/rolling applications where low friction is required. Due to these wide ranges of tribological applications, different surface combinations of mild steel have been selected in this research study. Within this research, it is sought to better understand the relation between friction/wear and different combinations of materials under different normal loads and sliding velocities and to explore the possibility of adding controlled normal load and sliding velocity to a mechanical process as a means to improve performance and quality in industry.

MATERIALS AND METHODS

A schematic diagram of the experimental set-up is shown in Fig. 1 i.e. a pin which can slide on a rotating horizontal surface (disc). In this set-up a circular test sample (disc) is to be fixed on a rotating plate (table) having a long vertical shaft clamped with screw from the bottom surface of the rotating plate. The shaft passes through two close-fit bush-bearings which are rigidly fixed with stainless steel plate and stainless steel base
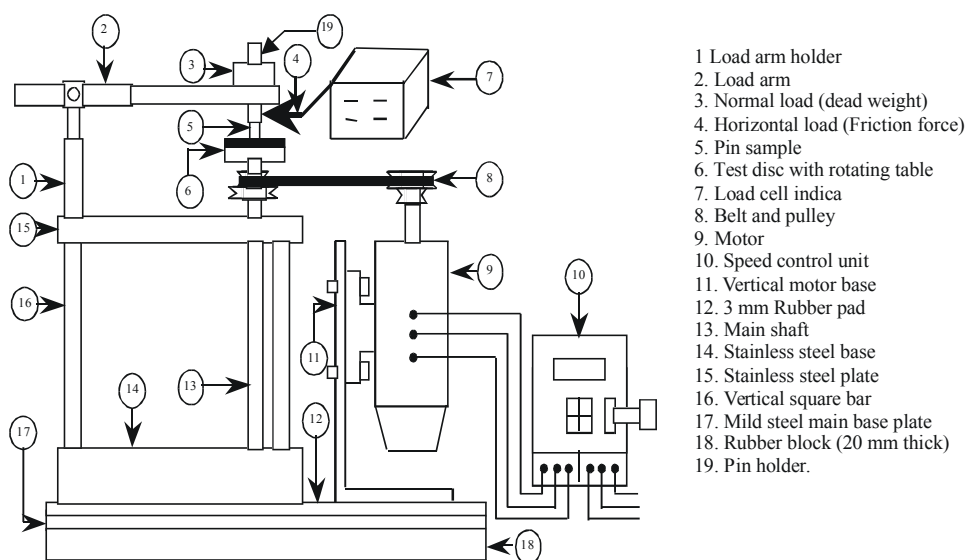
Fig. 1: Block diagram of the experimental set-up

1 Load arm holder
2. Load arm
3. Normal load (dead weight)
4. Horizontal load (Friction force)
5. Pin sample
6. Test disc with rotating table
7. Load cell indica
8. Belt and pulley
9. Motor
10. Speed control unit
11. Vertical motor base
12. 3 mm Rubber pad
13. Main shaft
14. Stainless steel base
15. Stainless steel plate
16. Vertical square bar
17. Mild steel main base plate
18. Rubber block (20 mm thick)
19. Pin holder.

Table 1: Experimental Conditions

Sl. No.	Parameters	Operating Conditions
1.	Normal Load	10, 15, 20 N
2.	Sliding Velocity	1, 1.5, 2 m/s
3.	Relative Humidity	70 ($\pm$ 5)%
4.	Duration of Rubbing	30 minutes
5.	Surface Condition	Dry
6.	Disc Material	Mild steel
7.	Disc Surface Condition	Turned and ground
8.	Roughness of Turned and Ground Mild Steel Disc, R_a	0.40-0.50 μm
9.	Pin Material	Mild steel
10.	Roughness of Mild Steel Pin, R_a	(a) Smooth counterface: 0.30-0.40 μm
		(b) Rough counterface: 3-4 μm

such that the shaft can move only axially and any radial movement of the rotating shaft is restrained by the bush. These stainless steel plate and stainless steel base are rigidly fixed with four vertical round bars to provide the rigidity to the main structure of this set-up. The main base of the set-up is constructed by 10 mm thick mild steel plate consisting of 3 mm thick rubber sheet at the upper side and 20 mm thick rubber block at the lower side. A compound V-pulley above the top stainless steel plate was fixed with the shaft to transmit rotation to the shaft from a motor. An electronic speed control unit is used to vary the speed of the motor as required. A 6 mm diameter cylindrical pin whose contacting foot is flat, made of mild steel, fitted on a holder is subsequently fitted with an arm. The arm is pivoted with a separate base in such a way that the arm with the pin holder can rotate vertically and horizontally about the pivot point with very low friction. Sliding speed can be varied by two ways (i) by changing the frictional radius and (ii) by changing the rotational speed of the shaft. In this research, sliding speed is varied

by changing the rotational speed of the shaft while maintaining 25 mm constant frictional radius. To measure the frictional force acting on the pin during sliding on the rotating plate, a load cell (TML, Tokyo Sokki Kenkyujo Co. Ltd, CLS-10NA) along with its digital indicator (TML, Tokyo Sokki Kenkyujo Co. Ltd, Model no. TD-93A) was used. The coefficient of friction was obtained by dividing the frictional force by the applied normal force (load). Wear was measured by weighing the test sample with an electronic balance before and after the test and then the difference in mass was converted to wear rate. To measure the surface roughness of the test samples, Taylor Hobson Precision Roughness Checker (Surtronic 25) was used. Each test was conducted for 30 minutes of rubbing time with new pin and test sample. Furthermore, to ensure the reliability of the test results, each test was repeated five times and the scatter in results was small, therefore the average values of these test results were taken into consideration. The detail experimental conditions are shown in Table 1.

RESULTS AND DISCUSSIONS

Variation of Friction Coefficient with Duration of Rubbing at Different Normal Loads: Figs. 2-5 show the variation of friction coefficient with the duration of rubbing and normal load for different types of disc-pin combinations. Figure 2 is drawn for ground surface of mild steel disc and smooth surface of mild steel pin. Curve 1 of this figure shows the value of friction coefficient of ground mild steel disc sliding against mild steel smooth pin for 10 N normal load. During the starting, value of friction coefficient is 0.292 which increases almost linearly up to 0.34 over a duration of 21 minutes of rubbing and after that it remains constant for the rest of the experimental time. Other curves of this figure show the values of friction coefficient at 15 and 20 N normal load. All these curves show similar trend as that of curve 1. Other parameters such as sliding velocity (1 m/s), surface roughness of disc (0.40-0.50 µm), surface roughness of pin (0.30-0.40 µm) and relative humidity (70%) are identical for these curves. The friction at the time of starting is low and the factors responsible for this low friction are due to the presence of a layer of foreign material. This surface in general comprises of (i) moisture, (ii) oxide of metals, (iii) deposited lubricating material, etc. Mild steel readily oxidizes in air, so that, at initial duration of rubbing, the oxide film easily separates the two metal surfaces and there is little or no true metallic contact and also the oxide film has a low shear strength. During initial rubbing, the film (deposited layer) breaks up and clean surfaces come in contact, which increase the bonding force between the contacting surfaces. At the same time due to the inclusion of trapped wear particles and roughening the substrate, the friction force increases due to the increase of ploughing effect. Increase of surface temperature, viscous damping of the friction surface, increased adhesion due to microwelding or deformation or hardening of the material might have some role on this increment of friction coefficient as well. After a certain duration of rubbing, the increase of roughness and other parameters may reach to a certain steady state value and hence the values of friction coefficient remain constant for the rest of the time. From the curves of Fig. 2, it is also observed that time to reach steady state values is different for different normal loads. Results show that at normal load 10, 15 and 20 N, mild steel takes 21, 19 and 16 minutes respectively to reach steady friction. It indicates that the higher the normal load, the time to reach steady friction is less. This is because the surface roughness and other parameter attain a steady level at a shorter period of time with the increase in normal load.

Figure 3 is drawn to show the variation of friction coefficient with the duration of rubbing at different normal loads for turned mild steel disc mating with smooth mild steel pin. Curve 1 of Fig. 3 is drawn for 10 N normal load shows that during starting of the running-in, the value of friction coefficient is 0.312 which increases for 19 minutes to a value of 0.363 and after that it remains constant for the rest of the experimental time. Similar trends of variation are observed for 15 and 20 N normal load which are shown in curves 2 and 3 respectively. From these curves, it is also observed that time to reach steady state values is different for different normal loads. Results show that at normal load 10, 15 and 20 N, mild steel takes 19, 17 and 14 minutes respectively to reach constant friction. It indicates that the higher the normal load, the time to reach constant friction is less. This is because the surface roughness and other parameter attain a steady level at a shorter period of time with the increase in normal load.

Variations of friction coefficient with duration of rubbing at different normal loads are shown in Figure 4 and in the experiments, ground mild steel disc mated with rough mild steel pin. For 10 N normal load (curve 1), friction coefficient is 0.23 at the initial stage of rubbing and after that friction coefficient increases steadily up to 0.274 over a duration of 20 minutes of rubbing and then which remains constant till experimental time 30 minutes. For normal load 15 and 20 N (curves 2 and 3), variations of friction coefficient are almost similar as that of curve 1. Also, mild steel disc takes about 20, 19 and 17 minutes to stabilize when the normal load are 10, 15 and 20 N respectively. From these obtained results it is clear that mild steel disc takes less time to reach steady state friction as the normal load increases.

Figure 5 is drawn to show the variation of friction coefficient with the duration of rubbing at different normal loads for turned mild steel disc mating with rough mild steel pin. Curve 1 of Fig. 5 is drawn for 10 N normal load shows that during starting of the running-in, the value of friction coefficient is 0.252 which increases for 21 minutes to a value of 0.304 and after that it remains constant for the rest of the experimental time. Similar trends of variation are observed for 15 and 20 N normal load which are shown in curves 2 and 3 respectively. From these curves, it is also observed that time to reach steady state values is different for different normal loads. Results show that at normal load 10, 15 and 20 N, mild steel takes 21, 19 and 17 minutes respectively to reach constant friction. It indicates that the higher the normal load, the time to reach constant friction is less.
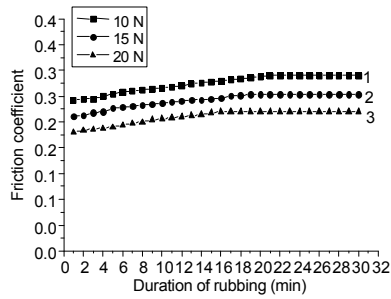
Fig. 2: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: mild Steel, ground pin: mild steel, smooth)
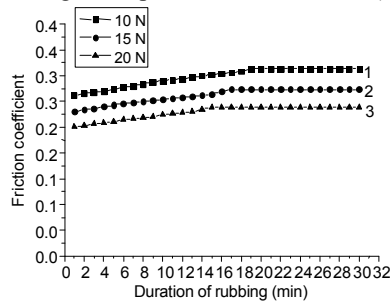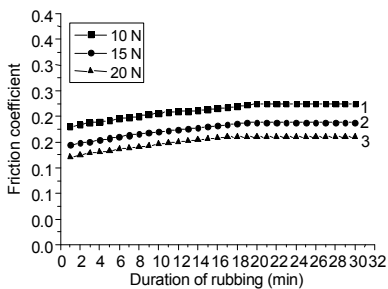

Fig. 3: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: mild steel, turned pin: mild steel, smooth)

Fig. 4: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: mild Steel, ground pin: mild steel, rough)

Influence of Normal Load on Friction Coefficient: Figure 6 shows the comparison of the variation of friction coefficient with normal load for different types of disc-pin combinations such as, ground-smooth, turned-smooth, ground-rough and turned-rough conditions. It is shown that friction coefficient varies from 0.34 to 0.27, 0.363 to 0.289, 0.274 to 0.21 and 0.304 to 0.22 with the variation of normal load from 10 to 20 N for ground-smooth, turned-smooth, ground-rough and turned-rough conditions respectively. The friction coefficient of all types of
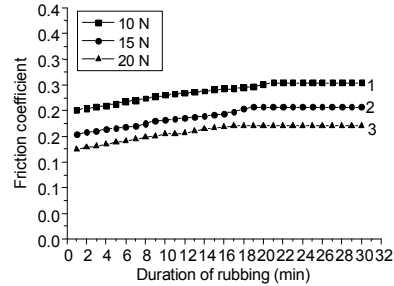

Fig. 5: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: mild steel, turned pin: mild steel, rough)
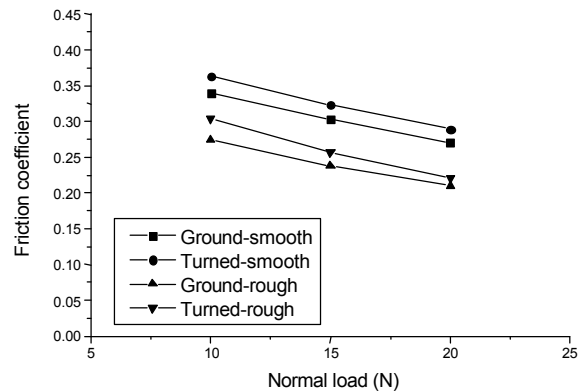

Fig. 6: Variation of Friction coefficient with the variation of normal loads at different pin-disc combinations (sliding velocity: 1 m/s, relative humidity: 70%)

combinations shows a decreasing trend with increasing load. At lower normal loads, the contact of the asperities is less and results in plowing action, increasing the friction coefficient. As the normal load increases, it results in better conformity of the contacting surfaces resulting in the reduced plowing action and friction coefficient. As the normal load is increased, an oxide layer may form on the surface due to rise of surface temperature and will provide lubricating action and reduce the friction [18]. Increased surface roughing and a large quantity of wear debris are also believed to be responsible for the decrease in friction [19,20] with the increase in normal load. Similar behavior is obtained for Al–Stainless steel pair [29] i.e. friction coefficient decreases with the increase in normal load. It can be noted that average roughness of mild steel turned and ground surface before run in process is 0.40 to 0.50 μm. The reduction of friction coefficient with normal load is also realized after the running-in process from the measured average values of surface roughness of mild steel disc for ground-smooth, turned-smooth, ground-rough and
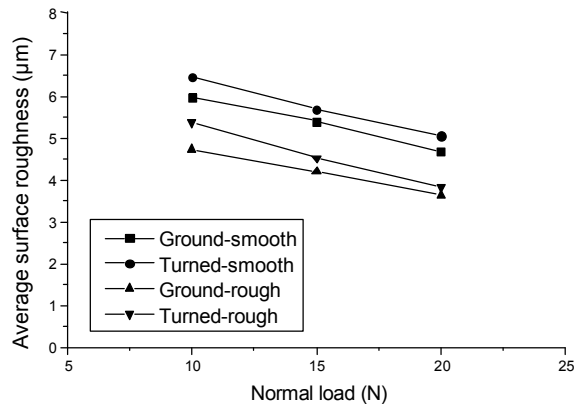
Fig. 7: Variation of average surface roughness with the variation of normal loads at different pin-disc combinations (sliding velocity: 1 m/s, relative humidity: 70%)
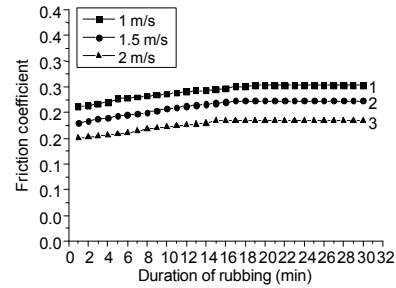

Fig. 8: Friction coefficient as a function of duration of rubbing at different sliding velocities (Normal load: 15 N, relative humidity: 70%, test sample: mild Steel, ground pin: mild steel, smooth)

turned-rough conditions. These results are presented in Fig. 7. From Fig. 7, it is found that the variations of average roughness of mild steel disc are 5.97, 5.4, 4.68 μm for ground-smooth sliding pairs, 6.46, 5.68 and 5.05 for turned-smooth sliding pairs, 4.73, 4.19 and 3.64 μm for ground-rough sliding pairs and 5.36, 4.52 and 3.82 μm for turned-rough sliding pairs with the variation of normal load 10, 15 and 20 N respectively. This means that higher the values of average surface roughness after friction test, the higher the values of friction coefficient are obtained. That is, higher normal load lower the average surface roughness hence lower the friction coefficient are obtained. At identical conditions, highest values of friction coefficient of mild steel disc are obtained for turned-smooth conditions. The lowest values of friction coefficient of mild steel disc are observed for ground-rough conditions. On the other hand, the values of friction coefficient of mild steel disc under ground smooth and turned-rough are found in between the highest and lowest values. It is noted that the friction coefficients of mild steel disc for turned-smooth conditions are higher than that of the ground-smooth conditions. It is also apparent that the values of friction coefficient of mild steel disc for turned-rough conditions are higher than that of ground-rough conditions. These trends of results are also validated by the measuring average surface roughness after run in process.

Variation of Friction Coefficient with Duration of Rubbing at Different Sliding Velocities: Friction coefficient varies with rubbing time and this variation at different sliding velocities shown in Figure 8.

In the experiment, ground mild steel disc mated with smooth mild steel pin at normal load 15 N, surface roughness of disc (0.40-0.50 μm), surface roughness of pin (0.30-0.40 μm) and relative humidity (70%). Results are shown by curves 1, 2 and 3 for 1, 1.5 and 2 m/s sliding velocity respectively. Curve 1 for sliding velocity 1 m/s shows that at the start of rubbing, friction coefficient is 0.261 and after that it increases very steadily up to 0.303. In the experiments, it was found that after 19 minutes of running-in operation, friction became steady. Due to the ploughing effect and surface roughening, friction increases. After a certain duration of running-in process, roughness and other parameters reached to steady state value and therefore, no change in frictional thrust till the experimental time. Fig. 8 (curves 2 and 3) it is apparent that friction coefficient is lower for increased sliding velocity but the trend is almost same as before. From the obtained results it can be noticed that time duration is different to reach steady friction depending on the sliding velocity. In the experiments, it was found that mild steel disc takes 19, 17 and 15 minutes to stabilize for sliding velocity 1, 1.5 and 2 m/s respectively. From these results it is understood that roughness and other parameters became steady earlier as the sliding velocity increased. Variations of friction coefficient with duration of rubbing at sliding velocity are shown in Figs. 9, 10 and 11 for turned-smooth, ground rough and turned-rough disc-pin combinations respectively. In the experiments, it was found that mild steel disc for turned-smooth conditions takes 17, 15 and 13 minutes to stabilize for sliding velocity 1, 1.5 and 2 m/s respectively. Under ground-rough conditions, mild steel disc takes 19, 17 and 15 minutes to stabilize for sliding velocity 1, 1.5 and 2 m/s respectively. In case of turned-rough conditions mild steel disc it takes 19, 17 and 15 minutes to stabilize for sliding velocity 1, 1.5 and 2 m/s respectively.
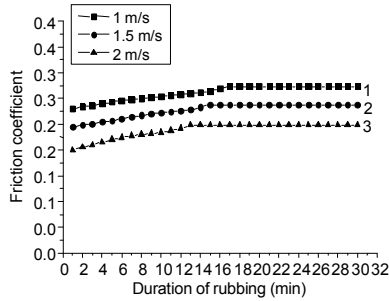
Fig. 9: Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N, relative humidity: 70%, test sample: mild Steel, turned pin: mild steel, smooth)
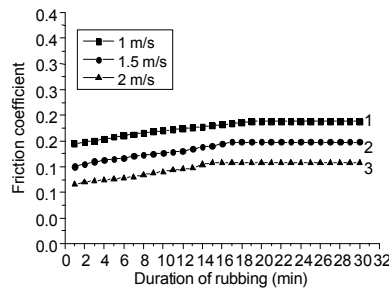

Fig. 10: Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N, relative humidity: 70%, test sample: mild Steel, ground pin: mild steel, rough)
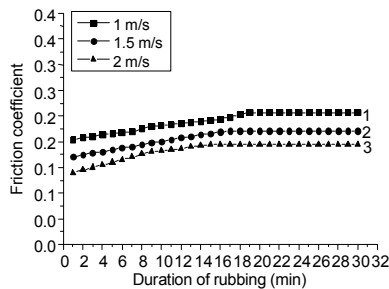

Fig. 11: Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N, relative humidity: 70%, test sample: mild Steel, turned pin: mild steel, rough)

Influence of Sliding Velocity on Friction Coefficient: Figure 12 shows the comparison of the variation of friction coefficient with sliding velocity for different types of disc-pin combinations such as, ground-smooth, turned-smooth, ground-rough and turned-rough conditions. It is shown that friction coefficient varies from 0.303 to 0.234, 0.323 to 0.248, 0.238 to 0.157 and 0.257 to 0.195 with the variation of sliding velocity from 1 to 2 m/s for ground-smooth, turned-smooth, ground-rough and turned-rough conditions respectively. The decrease of
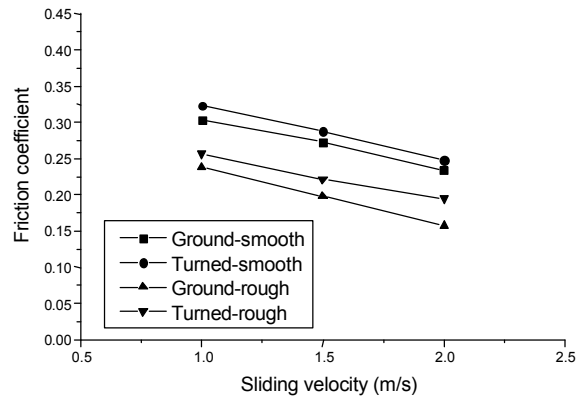

Fig. 12: Variation of Friction coefficient with the variation of sliding velocities at different pin-disc combinations (normal load: 15 N, relative humidity: 70%)

friction coefficient of above mentioned sliding pairs with the increase of sliding velocity may be due to the change in the shear rate which can influence the mechanical properties of the mating materials. The strength of these materials is greater at higher shear strain rates [14, 15] which results in a lower real area of contact and a lower coefficient of friction in dry contact condition. These findings are in agreement with the findings of Chowdhury and Helali [30] for mild steel, ebonite and GFRP sliding against mild steel. Similar trends of results The dependence of friction on velocity may also be explained in the following way. When velocity increases, momentum transfer in the normal direction increases producing an upward force on the upper surface. This results in an increased separation between the two surfaces which will decrease the real area of contact. Contributing to the increased separation is the fact that at higher speeds, the time during which opposite asperities compress each other is reduced increasing the level on which the top surfaces moves. Fig. 13 indicates that the variations of average roughness of mild steel disc are 5.4, 4.74 and 4.13 μm for ground-smooth sliding pairs, 5.68, 5.02 and 4.27 for turned-smooth sliding pairs, 4.19, 3.49 and 2.72 μm for ground-rough sliding pairs and 4.52, 3.87 and 3.14 μm for turned-rough sliding pairs with the variation of sliding velocity 1, 1.5 and 2 m/s respectively. This means that higher the values of average surface roughness after friction test, the higher the values of friction coefficient are obtained. That is, higher sliding velocity lower the average surface roughness hence lower the friction coefficient are obtained. At identical conditions, highest values of friction coefficient of mild steel disc are obtained for turned-smooth conditions. The lowest values
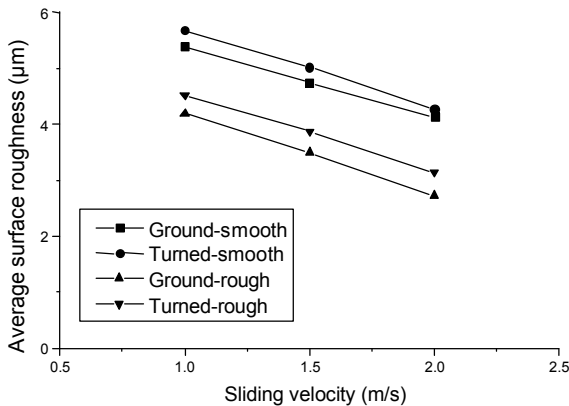
Fig. 13: Variation of average surface roughness with the variation of sliding velocities at different pin-disc combinations (normal load: 15 N, relative humidity: 70%)
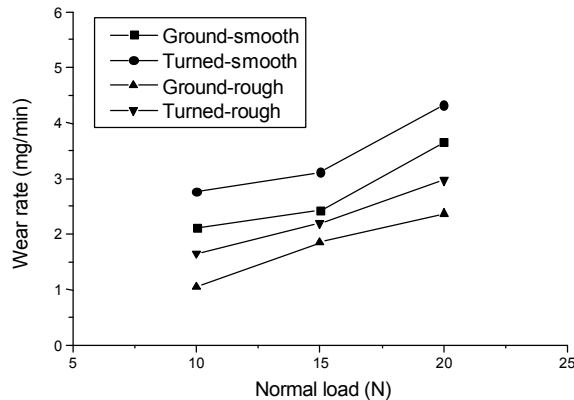

Fig. 14: Variation of wear rate with the variation of normal loads at different pin-disc combinations (sliding velocity: 1 m/s, relative humidity: 70%)
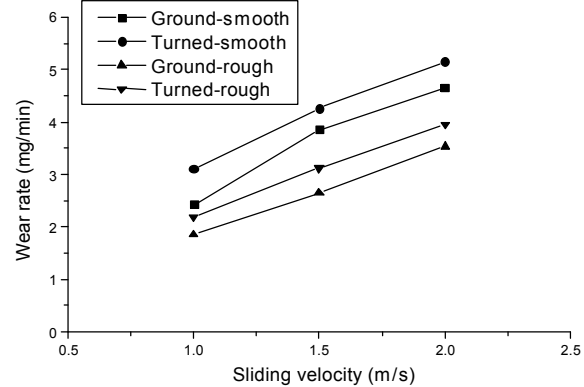

Fig. 15: Variation of wear rate with the variation of sliding velocities at different pin-disc combinations (normal load: 15 N, relative humidity: 70%)

of friction coefficient mild steel disc are observed for ground-rough conditions. On the other hand, the values of friction coefficient of mild steel disc under ground smooth and turned-rough are found in between the highest and lowest values. It is noted that the friction coefficients of mild steel disc for turned-smooth conditions are higher than that of the ground-smooth conditions. It is also apparent that the values of friction coefficient of mild steel disc for turned-rough conditions are higher than that of ground-rough conditions. These trends of results are also validated by the measuring average surface roughness after run in process.

Influence of Normal Load on Wear Rate: Variations of wear rate with normal load are presented in Fig. 14. Results show that wear rate of mild steel disc varies from

2.11 to 3.65, 2.76 to 4.33, 1.05 to 2.36 and 1.65 to 2.97 mg/min with the variation of normal load from 10 to 20 N for different types of disc-pin combinations such as, ground-smooth, turned-smooth, ground-rough and turned-rough conditions respectively. It is observed that wear rate increases with the increase in normal load for all of the material combinations. When the load on the pin is increased, the actual area of contact would increase towards the nominal contact area, resulting in increased frictional force between two sliding surfaces. The increased frictional force and real surface area in contact causes higher wear. This means that the shear force and frictional thrust are increased with increase of applied load and these increased in values accelerate the wear rate. Similar trends of variation are also observed for mild steel–mild steel couples [31], i.e wear rate increases with the increase in normal load. From this figure, it is also found that at identical conditions, highest values of wear rate of mild steel disc are obtained for turned-smooth conditions. The lowest values of wear rate mild steel disc are observed for ground-rough conditions. On the other hand, the values of wear rate of mild steel disc under ground-smooth and turned-rough are found in between the highest and lowest values. It is noted that the wear rates of mild steel disc for turned-smooth conditions are higher than that of the ground-smooth conditions. It is also apparent that the values of wear rate of mild steel disc for turned-rough conditions are higher than that of ground-rough conditions.

Influence of Sliding Velocity on Wear Rate: The variations of wear rate with sliding velocity for above mentioned material combinations are also observed in this study and the results are presented in Fig. 15.

Table 2: Friction coefficient at different normal loads and sliding velocities for different surface conditions (disc-pin combinations)

| | | Friction coefficient (μ) | | | |
| | | Surface condition (disc-pin combinations) | | | |
Sliding velocity (m/s)	Normal load (N)	Ground-Smooth	Turned-Smooth	Ground-Rough	Turned-Rough
1	10	0.34	0.363	0.274	0.304
1.5		0.313	0.323	0.245	0.264
2		0.273.	0.284	0.216	0.235
1	15	0.303	0.323	0.238	0.257
1.5		0.273	0.288	0.198	0.221
2		0.234	0.248	0.157	0.195
1	20	0.27	0.289	0.21	0.22
1.5		0.215	0.235	0.157	0.186
2		0.16	0.196	0.108	0.137

Table 3: Average roughness after run in process at different normal loads and sliding velocities for different surface conditions (disc-pin combinations)

| | | Average roughness after run in process (μm) | | | |
| | | Surface condition (disc-pin combinations) | | | |
Sliding velocity (m/s)	Normal load (N)	Ground-Smooth	Turned-Smooth	Ground-Rough	Turned-Rough
1	10	5.97	6.46	4.73	5.36
1.5		5.4	5.66	4.25	4.63
2		4.73	4.93	3.74	4.09
1	15	5.40	5.68	4.19	4.52
1.5		4.74	5.02	3.49	3.87
2		4.13	4.27	2.72	3.14
1	20	4.68	5.05	3.64	3.82
1.5		3.78	4.14	2.76	3.26
2		2.83	3.45	1.92	2.43

Table 4: Wear rate at different normal loads and sliding velocities for different surface conditions (disc-pin combinations)

| | | Wear rate (mg/min) | | | |
| | | Surface condition (disc-pin combinations) | | | |
Sliding velocity (m/s)	Normal load (N)	Ground-Smooth	Turned-Smooth	Ground-Rough	Turned-Rough
1	10	2.11	2.76	1.05	1.65
1.5		3.30	3.47	2.15	2.85
2		4.2	4.63	3.12	3.67
1	15	2.42	3.11	1.85	2.19
1.5		3.85	4.26	2.65	3.12
2		4.65	5.15	3.54	3.95
1	20	3.65	4.33	2.36	2.97
1.5		4.28	5.34	2.91	3.85
2		5.12	6.17	4.01	4.71

These results indicate that wear rate of mild steel disc varies from 2.42 to 4.65, 3.11 to 5.15, 1.85 to 3.54 and 2.19 to 3.95 mg/min with the variation of sliding velocity from 1 to 2 m/s for ground-smooth, turned-smooth, ground-rough and turned-rough disc-pin couples respectively. It is observed that wear rate increases with the increase in sliding velocity for all of these material pairs. This is due to the fact that duration of rubbing is same for all sliding velocities, while the length of rubbing is more for higher sliding velocity. The reduction of shear strength of the material and increased true area of contact between contacting surfaces may have some role on the higher wear rate at higher sliding velocity [13]. From this figure, it is also observed that at identical conditions, highest values of wear rate of mild steel disc are obtained for turned-smooth conditions. The lowest values of wear rate
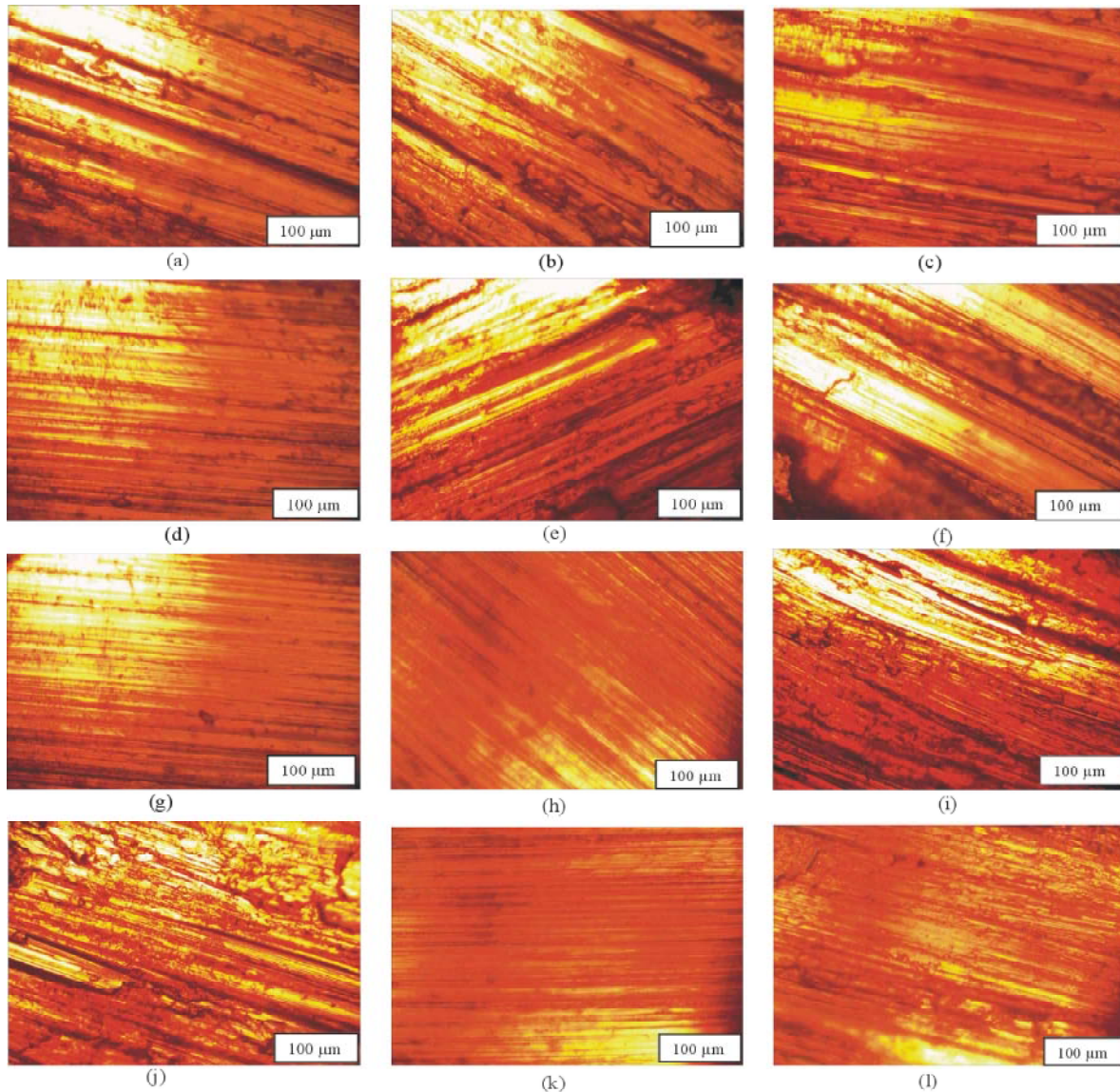
Fig. 16: Optical microscopy of worn surfaces of mild steel for (a) Turned-smooth (10 N, 1 m/s) (b) Ground-smooth (10 N, 1 m/s) (c) Turned-rough (10 N, 1 m/s) (d) Ground-rough (10 N, 1 m/s) (e) Turned-smooth (20 N, 1 m/s) (f) Ground-smooth (20 N, 1 m/s) (g) Turned-rough (20 N, 1 m/s) (h) Ground-rough (20 N, 1 m/s) (i) Turned-smooth (10 N, 2 m/s) (j) Ground-smooth (10 N, 2 m/s) (k) Turned-rough (10 N, 2 m/s) (l) Ground-rough (10 N, 2 m/s)

mild steel disc are observed for ground-rough conditions. On the other hand, the values of wear rate of mild steel disc under ground-smooth and turned-rough are found in between the highest and lowest values. It is noted that the wear rates of mild steel disc for turned-smooth conditions are higher than that of the ground-smooth conditions. It is also apparent that the values of wear rate of mild steel disc for turned-rough conditions are higher than that of ground-rough conditions.

Friction Coefficient, Wear Rate and Average Surface Roughness at Different Normal Loads and Sliding Velocities: Friction coefficient, average surface roughness (after run in process) and wear rate are shown in Tables 2, 3 and 4. From Tables 2 and 3, it is observed that friction coefficient and average surface roughness (after run in process) decrease with the increase in normal load and sliding velocity. On the other hand, Table 4 indicates wear rate increases with the increase in normal load and sliding velocity.

Analysis of Worn Surfaces: Figure 16 shows the optical pictures of the worn surfaces for different combinations of sliding pairs. The appearance of the worn surface of mild steel for turned-smooth disc-pin combinations is clearly rougher than that of ground-smooth disc-pin combinations. In contrast, the wear tracks of mild steel for turned-rough and ground-rough couples are less rough and free from adhered material. From these photographs, it is also confirmed that the higher the normal load and sliding velocity less rougher the mild steel surfaces for different sliding pairs are observed. It can be noted that these observations are also ensured by measured roughness values of mild steel for different combinations. The optical microscopy studies of wear surface show abrasive and adhesion wear on the surface of mild steel for different combinations. The debonding/pullout of the particles are also seen. The particle reinforcement significantly improved wear resistance. The experimental observations indicate that the main wear mechanism for the mild steel of different sliding pairs is the combination of wear, abrasive and delamination.

CONCLUSION

The presence of normal load, sliding velocity and surface conditions of disc and pin indeed affects the friction force considerably. Within the observed range, the values of friction coefficient decrease with the increase in normal load and sliding velocity for turned or ground mild steel sliding against smooth or rough mild steel pin. Friction coefficient varies with the duration of rubbing and after certain duration of rubbing, friction coefficient becomes steady for the observed range of normal load and sliding velocity. Wear rates of turned or ground mild steel mating with smooth or rough mild steel counterface increase with the increase in normal load and sliding velocity. At identical conditions, within the observed range of normal load and sliding velocity, highest values of friction coefficient and wear rate of mild steel disc are obtained for turned-smooth conditions. The lowest values of friction coefficient and wear rate of mild steel disc are observed for ground-rough conditions. On the other hand, the values of friction coefficient and wear rate of mild steel disc under ground-smooth and turned-rough are found in between the highest and lowest values. The friction coefficients and wear rates of mild steel disc for turned-smooth conditions are higher than that of the ground-smooth conditions. The values of friction coefficient and wear rate of mild steel disc for turned-rough conditions are higher than that of ground-rough conditions. The higher the normal load and sliding velocity lower the average surface roughness (after run in process) hence lower the friction coefficient are obtained.

As (i) the friction coefficient decreases with the increase in normal load and sliding velocity, (ii) wear rate increases with the increase in normal load and sliding velocity and (iii) the magnitudes of friction coefficient and wear rate are different for different sliding pairs, therefore maintaining an appropriate level of normal load, sliding velocity as well as appropriate choice of sliding pairs and surface conditions, friction and wear may be kept to some lower value to improve mechanical processes.

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